



THE HENRYK NIEWODNICZAŃSKI  
INSTITUTE OF NUCLEAR PHYSICS  
POLISH ACADEMY OF SCIENCES



## Perturbative QCD in Quarkonium Production (PQQP)

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*IFJ PAN - IJCLab meeting, Orsay,  
07 December 2023*

## IJCLab team

- Staff:
  - Jean-Philippe Lansberg (CNRS DR)
  - Melih Ozcelik (CNRS CR)
  - Samuel Wallon (Prof.)
- Post-doc:
  - Christopher Flett (post-doc)
  - Michael Fucilla (post-doc)
  - Saad Nabeebaccus (post-doc)
  - Maxim Nefedov (post-doc)
- PhD student:
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# IFJ PAN - Research & Publications:

Nuclear Theory: reaction theory, nuclear fission, photoexcitation of nuclei, ultraperipheral heavy ion collisions

Strong Interaction Phenomenology: hard and soft diffractive processes, unintegrated parton distributions, nuclear modifications of hard processes, quarkonium structure and production, exotic meson production, double parton scattering, open heavy flavor production, bremsstrahlung, soft photon theorems

Selected Publications:

- [1] I. Babiarczyk, W. Schäfer, A. Szczurek, **Associated production of  $\chi_c$  pairs with a gluon in the collinear-factorization approach**, Phys.Rev.D 99 (2019) 7, 074014, e-Print: 1902.08426 [hep-ph]
- [2] A. Cisek, W. Schäfer, A. Szczurek, **Production of  $\chi_c$  pairs in  $k_T$ -factorization**, Phys.Rev.D 97 (2018) 11, 114018, e-Print: 1711.07366 [hep-ph]
- [3] S. Baranov, A. Cisek, M. Klusek-Gawenda, W. Schäfer, A. Szczurek, **The  $\gamma\gamma \rightarrow J/\psi J/\psi$  reaction and the  $J/\psi J/\psi$  pair production in exclusive ultraperipheral ultrarelativistic heavy ion collisions**, Eur.Phys. J.C 73 (2013) 2, 2335, e-Print: 1208.5917 [hep-ph]
- [4] R. Maciuła, A. Szczurek, A. Cisek,  **$J/\psi$ -meson production within improved color evaporation model with the  $k_T$ -factorization approach for  $c\bar{c}$  production**, Phys.Rev.D 99 (2019) 5, 054014, e-Print: 1810.08063 [hep-ph]
- [5] R. Maciuła, A. Szczurek, **Double-parton scattering effects in  $D^0 B^+$  and  $B^+ B^+$  meson-meson pair production in proton-proton collisions at the LHC**, Phys.Rev.D 97 (2018) 9, 094010, e-Print: 1803.01198 [hep-ph]

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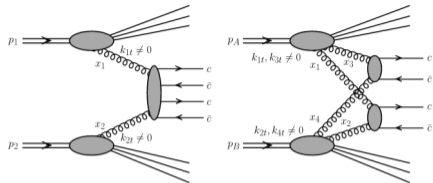
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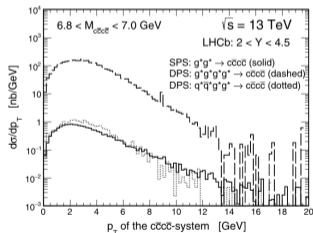
Selected Publications:

- [6] R. Maciuła, W. Schäfer, A. Szczurek, **On the mechanism of  $T_{4c}$  (6900) tetraquark production**, Phys.Lett.B 812 (2021) 136010, e-Print: 2009.02100 [hep-ph]
- [7] I. Babiarez, R. Pasechnik, W. Schäfer, A. Szczurek, **Central exclusive production of scalar and pseudoscalar charmonia in the light-front  $k_T$ -factorization approach**, Phys.Rev.D 102 (2020) 114028, e-Print: 2008.05462 [hep-ph]
- [8] I. Babiarez, R. Pasechnik, W. Schäfer, A. Szczurek, **Hadroproduction of scalar P-wave quarkonia in the light-front  $k_T$ -factorization approach**, JHEP 06 (2020) 101, e-Print: 2002.09352 [hep-ph]
- [9] I. Babiarez, V. P. Goncalves, R. Pasechnik, W. Schäfer, A. Szczurek,  **$\gamma\gamma \rightarrow \eta_c$  transition form factors for spacelike photons**, Phys.Rev.D 100 (2019) 5, 054018, e-Print: 1908.07802 [hep-ph]
- [10] I. Babiarez, R. Pasechnik, W. Schäfer, A. Szczurek, **Prompt hadroproduction of  $\eta_c(1S,2S)$  in the  $k_T$ -factorization approach** JHEP 02 (2020) 037, e-Print: 1911.03403 [hep-ph]

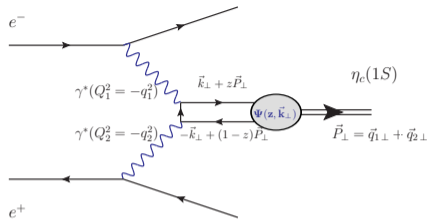
# IFJ PAN - selected results on Quarkonium physics



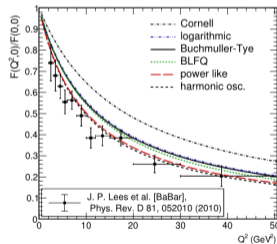
Two dominant reaction mechanisms of production of  $c\bar{c}c\bar{c}$  nonresonant continuum. The left diagram represents the SPS mechanism (box type) and the right diagram the DPS mechanism, see Ref. [6].



Distribution of  $p_{T,4c}$  of four quark-antiquark system within invariant mass window ( $M_R - 0.1$  GeV,  $M_R + 0.1$  GeV). Here  $\sqrt{s} = 13$  TeV and average rapidity of quarks and antiquarks in the interval (2, 4.5), see Ref. [6].

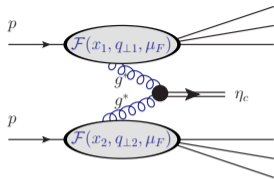


$\eta_c$  production by  $\gamma^* \gamma^*$  interactions

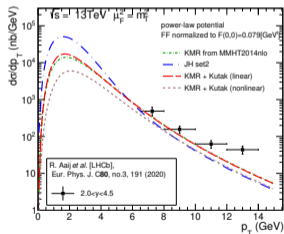


Dependence of the normalised transition form factor,  $F(Q^2, 0)/F(0, 0)$ , on the photon virtuality  $Q^2$  predicted by the different potential models. The prediction of the Basis Light Front Approach and the BaBar data are also presented for comparison. From Ref. [9].

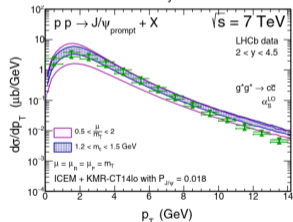
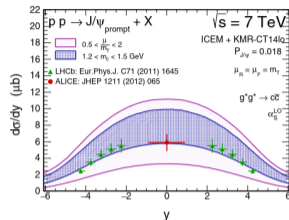
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$\eta_c$  production in proton-proton collisions via gluon-gluon subprocess. Here  $\mathcal{F}(x_{1;2}, q_{\perp 1;2}, \mu_F)$  are **unintegrated gluon distribution functions**, which depend on incoming gluon transverse momenta  $q_{\perp 1;2}$ .



Differential cross-section in transverse momentum of  $\eta_c(1S)$  at  $\sqrt{s} = 13$  TeV within  $2.0 < y < 4.5$  compared to LHCb data. The power-law potential model normalized to decay width is used for several **unintegrated gluon distribution functions**. From Ref. [10].



Distributions in rapidity and transverse momentum of prompt  $J/\psi$  for  $\sqrt{s} = 7$  TeV obtained within the  $k_T$ -factorization realization of the **improved color evaporation model ICEM**. The shaded bands represent uncertainties of our model due to the variation of the default set of the scales and of the charm quark mass. From Ref. [4].

Strong Interaction Phenomenology: perturbative QCD, higher-order perturbative corrections, master integral calculation, hard and soft diffractive processes, saturation physics, nuclear PDF determination, quarkonium phenomenology, double parton scattering, TMD factorisation, high-energy factorisation

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- [1] S. Abreu, M. Becchetti, C. Duhr, M.A. Ozelik, **Two-loop form factors for pseudo-scalar quarkonium production and decay**, JHEP 02 (2023) 250, e-Print: 2211.08838 [hep-ph]
- [2] K.J. Eskola, C. Flett, V. Guzey, T. Loytainen, H. Paukkunen, **Predictions for exclusive  $\Upsilon$  photoproduction in ultraperipheral Pb+Pb collisions at the LHC at next-to-leading order in perturbative QCD**, Eur.Phys.J.C 83 (2023) 8, 758, e-Print: 2303.03007 [hep-ph]
- [3] D. Boer, J. Bor, L. Maxia, C. Pisano, F. Yuan, **Transverse momentum dependent shape function for  $J/\psi$  production in SIDIS**, JHEP 08 (2023) 105, e-Print: 2304.09473 [hep-ph]
- [4] J.-P. Lansberg, M.A. Nefedov, M.A. Ozelik, **Curing the high-energy perturbative instability of vector-quarkonium-photoproduction cross sections at order  $\alpha\alpha_s^3$  with high-energy factorisation**, e-Print: 2306.02425 [hep-ph]
- [5] J.-P. Lansberg, M.A. Ozelik, **Curing the unphysical behaviour of NLO quarkonium production at the LHC and its relevance to constrain the gluon PDF at low scales**, Eur.Phys.J.C 81 (2021) 6, 497, e-Print: 2012.00702 [hep-ph]

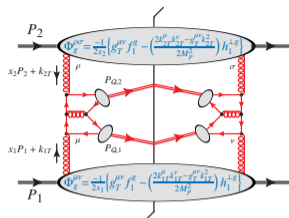
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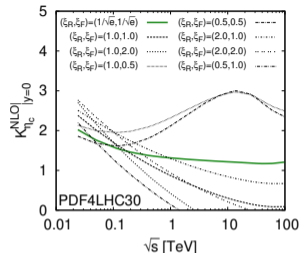
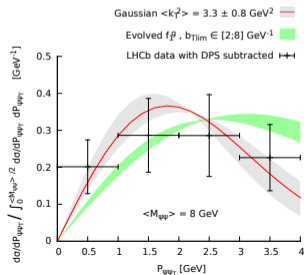
- [6] A. Colpani Serri, Y. Feng, C. Flore, J.-P. Lansberg, M.A. Ozelik, H.-S. Shao, Y. Yedelkina, **Revisiting NLO QCD corrections to total inclusive  $J/\Psi$  and  $\Upsilon$  photoproduction cross sections in lepton-proton collisions**, Phys.Lett.B 835 (2022) 137556, e-Print: 2112.05060 [hep-ph]
- [7] Z.-G. He, B.A. Kniehl, M.A. Nefedov, V.A. Saleev, **Double Prompt  $J/\Psi$  Hadroproduction in the Parton Reggeization Approach with High-Energy Resummation**, Phys.Rev.Lett. 123 (2019) 16, 162002, e-Print: 1906.08979 [hep-ph]
- [8] R. Boussarie, B. Ducloué, L. Szymanowski, S. Wallon, **Forward  $J/\Psi$  and very backward jet inclusive production at the LHC**, Phys.Rev.D 97 (2018) 1, 014008, e-Print: 1709.01380 [hep-ph]
- [9] J.-P. Lansberg, H.-S. Shao,  **$J/\Psi$ -pair production at large momenta: Indications for double parton scatterings and large  $\alpha_s^5$  contributions**, Phys.Lett.B 751 (2015) 479-486, e-Print: 1410.8822 [hep-ph]
- [10] F. Scarpa, D. Boer, M.G. Echevarria, J.-P. Lansberg, C. Pisano, M. Schlegel, **Studies of gluon TMDs and their evolution using quarkonium-pair production at the LHC**, Eur.Phys.J.C 80 (2020) 2, 87, e-Print: 1909.05769 [hep-ph]



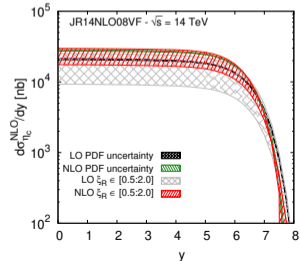
# IJCLab - selected results on Quarkonium physics



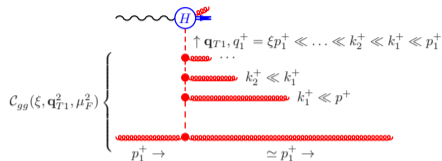
Study of  $J/\psi$  pair production at  $pp$  collision within Transverse-Momentum-Dependent (TMD) factorisation (graph above). The small transverse momentum distribution of the  $J/\psi$  pair is predicted using different TMD evolution models (graph below), see Ref. [10].



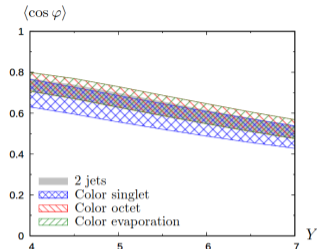
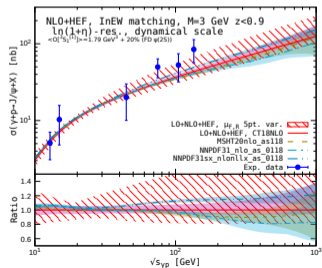
$\eta_c$  hadroproduction within collinear factorisation. Next-To-Leading Order (NLO) QCD calculation yields large scale uncertainties (see above). A new scale prescription for factorisation scale choice yields reliable results, see graph below for rapidity distribution. From Ref. [5]



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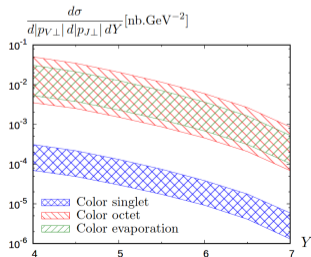


Study of  $J/\psi$  photoproduction within collinear and high-energy factorisation (HEF) (see graph above). A new matching approach combining both collinear and HEF contributions yields to results close to experimental data (see below). From Ref. [4].



$0 < y_V < 2.5, -4.5 < y_J < 0, p_{\perp} = 20 \text{ GeV}$

$J/\psi$  + jet production in  $pp$  collisions at large rapidity separation  $Y$  using BFKL formalism. From Ref. [8].



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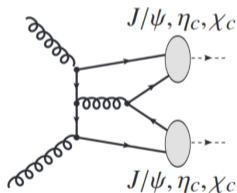
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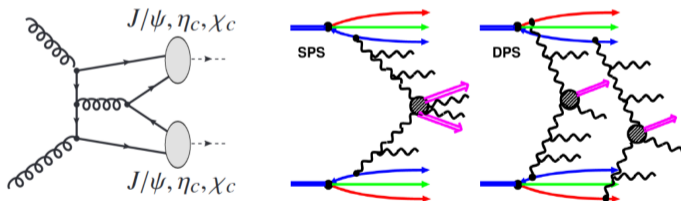


$J/\psi$  pair production in  $pp$  collisions at large rapidity separation  $Y$ . Right plots shows prompt  $J/\psi$  pair production within HEF factorisation [7], there is discrepancy with CMS data.

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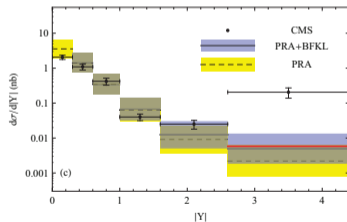
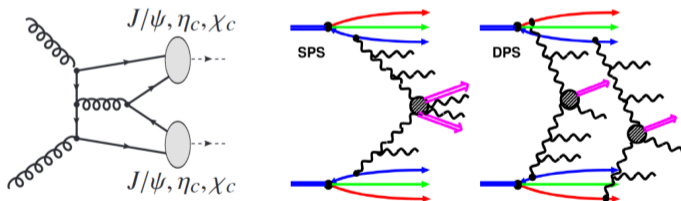
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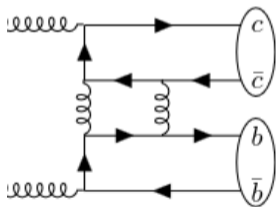
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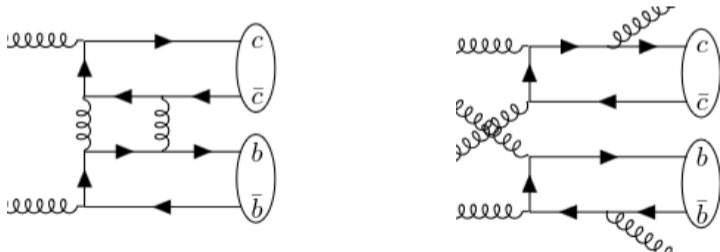


$J/\psi + \Upsilon$  production in  $pp$  collisions. New data available at LHCb. In order to describe  $p_T$  distribution and azimuthal correlation of the pair, TMD factorisation approach can be used. For  $J/\psi + J/\psi$  TMD study case, see [10].

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  - 4000€ travel for IFJ PAN members to visit Orsay
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  - maybe in future, shared post-doc(s) to strengthen collaboration?



Thank you for attention!